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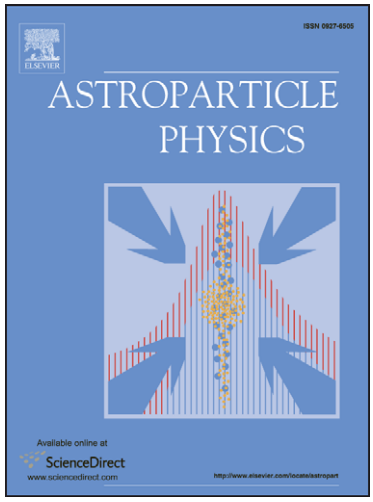

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PII: S0927-6505(11)00002-8
DOI: 10.1016/j.astropartphys.2010.12.013
Reference: ASTPHY 1561

To appear in: *Astroparticle Physics*

Received Date: 20 October 2010
Revised Date: 7 December 2010
Accepted Date: 30 December 2010

Please cite this article as: Y. Ortigoza, N. Coron, C. Cuesta, E. García, C. Ginestra, J. Gironnet, P. de Marcillac, M. Martínez, C. Pobes, J. Puimedón, T. Redon, M.L. Sarsa, L. Torres, J.A. Villar, Energy partition in Sapphire and BGO scintillating bolometers, *Astroparticle Physics* (2011), doi: 10.1016/j.astropartphys.2010.12.013

Energy partition in Sapphire and BGO scintillating bolometers

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Abstract

Scintillating bolometers are particle detectors with a high particle discrimination power with many applications in nuclear and particle physics. This discrimination power is based on the different scintillation yield for different particles, and is strongly dependent on the target used. At the very low temperatures required for the operation of the bolometers, very few data about the scintillation yields are available. In this paper we present estimates of absolute light yields and energy partition among heat, light and trapping channels in Sapphire (Al_2O_3) and BGO ($Bi_4Ge_3O_{12}$) scintillating bolometers operated at 20 mK. The estimate relies on the observed negative correlation between the light and heat signals produced by γ–ray absorption in scintillating bolometers and on the study of the x–ray stimulated luminescence properties of BGO at temperatures down to 77 K.

Keywords:
Cryogenic detector, Scintillating bolometer, Energy partition, Light yield, Dark matter

1. Introduction

Bolometers are cryogenic detectors widely used in the last decades (see for instance [1, 2]) which measure as heat the energy deposited by particle interactions. They consist of an absorber where interacting particles deposit energy producing an increase of temperature ΔT and a thermal sensor (thermally connected to the absorber on one side and to a thermal bath via a heat leak on the other side) where ΔT is converted into an electrical signal. Massive bolometers can be built with dielectric and diamagnetic crystals cooled at temperatures of a few millikelvin because their heat capacity, which is only ascribed to vibrations of the crystal lattice and depends on the cube of the temperature, can be low enough to produce a measurable ΔT.

The simultaneous measurement of heat and light signals was proposed in 1988 as a new tool for particle detection [3]: the very different scintillation yield of different particles (β/γ particles, α particles and other recoiling nuclei) could be used to identify the type of particle, whereas the heat signal could allow to estimate the deposited energy with high resolution. The viability of this technique was shown in 1992 by the Milano group [4] using a Si photodiode glued on a CaF_2(Eu) bolometer to measure scintillation photons. In 1997 a French group [5] developed a new technique for the detection of scintillation photons using a second bolometer. This double bolometer technique is currently being used by the ROSEBUD Collaboration [6], the CRESST Dark Matter Search Experiment [7] and the Milano Group [8] and applied to rare event searches as double beta decay and dark matter.

ROSEBUD (Rare Objects SEarch with Bolometers UndergrounD) is a collaboration between the Universidad de Zaragoza and the Institut d'Astrophysique Spatiale (IAS), which develops and tests different materials as scintillating bolometer prototypes in order to apply them as detectors in nuclear and particle physics, with special emphasis on dark matter searches. Scintillating bolometers of Al_2O_3, BGO, $CaWO_4$ and LiF among others, have been developed and characterized by ROSEBUD (see for instance [6, 9]). This work refers to a 50 g Al_2O_3 and a 46 g BGO scintillating

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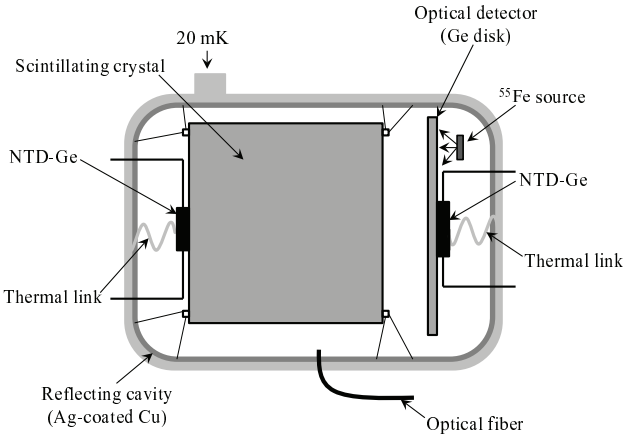

Figure 1: Schematic view of a double bolometer configuration. For the measurements presented in this work an inner ^{55}Fe x–ray source was placed opposite the Ge bolometer to calibrate the energy absorbed on it.

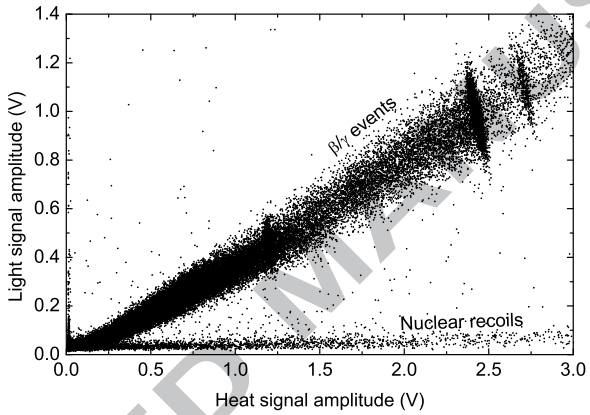

Figure 2: Light versus heat discrimination plot obtained with the Al_2O_3 scintillating bolometer [10]. The lines of 59.5 keV (from a ^{241}Am source), 122.1 and 136.5 keV (from a ^{57}Co source) are clearly seen in the β/γ band at values (in the heat channel) around 1.2, 2.4 and 2.7 V and show a negative correlation between the light and heat pulse amplitudes. A similar behaviour is observed in the BGO [11].

bolometers. As shown in figure 1, these scintillating bolometers consist of a scintillating crystal (Al_2O_3 or BGO) and a small Ge disk looking at the scintillating crystal, both mounted inside a copper cavity internally coated with Ag to obtain a good reflectivity. The scintillating crystal and the Ge disk have each one a neutron transmutation doped (NTD) Ge thermistor glued to it in order to measure thermal increases. The heat produced in the scintillating crystal is directly measured by its NTD–Ge sensor and the emitted light escaping from it that is eventually absorbed in the Ge crystal produces a thermal increase that is measured by the other NTD-Ge sensor. The double bolometers are thermally coupled to the mixing chamber of a dilution refrigerator operated at 20 mK. For technical details about the design, experimental set-up and operation of scintillating bolometers see [10, 11] and references therein.

Events in scintillating bolometers can be represented by points in a light versus heat pulse amplitude scatter plot. In these plots, monoenergetic events like those due to full absorption of γ–rays of a given energy appear as binormal distributions (see figure 2). Both channels, if independent, should not be correlated but we observed, first in a nominally pure Sapphire crystal [10] (with a measured Ti concentration of 6 ppm [12]) and then in a nominally pure BGO crystal [11], a negative correlation between the light and heat signals of these binormal distributions (see table 1) pointing at some energy transfer from one to the other channel. The same effect has also been noticed in a $CdWO_4$ scintillating bolometer tested by members of the CUORICINO/CUORE Collaboration for Double Beta Decay experiments [13] and also in a dual phase liquid–gas Xe dark matter detector [14].

In reference [10] we proposed a quantitative interpretation of this correlation: for a given energy, the mean voltage outputs in the light and heat signals are directly related to the fraction of the deposited energy initially converted into light, α_ℓ (we will refer to it as the absolute light yield), and the fraction of the deposited energy initially converted into heat, α_h, respectively; the correlation coefficient originated by an energy transfer from one channel to the other is independent of α_ℓ and α_h; taking advantage of that, from these values one can estimate the ratio α_ℓ/α_h. This method, developed for the Al_2O_3 scintillating bolometer was subsequently applied to the BGO scintillating bolometer [11]. Table 1 shows the values derived in both bolometers for the ratio α_ℓ/α_h at different γ–ray energies. One can observe that, in the range of energies analyzed, values obtained for α_ℓ/α_h in each scintillating bolometer are compatible with a constant value, independent of the energy, with weighted mean 0.144 ± 0.010 and 0.125 ± 0.021 for Sapphire and BGO, respectively.

Table 1: Correlation coefficient (ρ) between heat and light pulse amplitudes on full absorption γ–ray lines and the derived ratio between the fraction of the deposited energy initially converted into light α_ℓ and into heat α_h for scintillating bolometers of Sapphire and BGO operated at 20 mK. [a]The line of 1633.3 keV corresponds to a measurement made in different experimental conditions (lower gain). The first and second errors given for α_ℓ/α_h correspond to the statistic and systematic ones, respectively. Data taken from [10] for Al_2O_3 and [11] for BGO.

	Energy (keV)	ρ	α_ℓ/α_h
Al_2O_3	59.5	-0.61 ± 0.02	$0.111 \pm 0.006 \pm 0.037$
	122.1	-0.890 ± 0.005	$0.146 \pm 0.004 \pm 0.012$
	136.5	-0.87 ± 0.01	$0.148 \pm 0.009 \pm 0.015$
BGO	88.0	-0.24 ± 0.02	$0.145 \pm 0.004 \pm 0.073$
	351.9	-0.39 ± 0.05	$0.124 \pm 0.010 \pm 0.045$
	569.7	-0.29 ± 0.03	$0.157 \pm 0.009 \pm 0.070$
	609.3	-0.27 ± 0.07	$0.103 \pm 0.012 \pm 0.049$
	657.7	-0.54 ± 0.06	$0.119 \pm 0.013 \pm 0.030$
	1633.3[a]	-0.21 ± 0.08	$0.153 \pm 0.021 \pm 0.082$

In these previous works, assuming that all the deposited energy is converted into heat and light (i.e., $\alpha_\ell + \alpha_h = 1$), we have estimated absolute light yield for photons (0.127 ± 0.010 in Sapphire [10] and 0.112 ± 0.016 in BGO [11]). This is an optimistic assumption because there are energy relaxation mechanisms (like, for instance, energy stored in traps living larger than a few milliseconds) that do not contribute to the heat or light signal, and, as explained in reference [10], estimates of the light yields should be properly rescaled (obtaining lower values). This paper reports the results of the study of the scintillation spectra of BGO down to 77 K which allows us to estimate the absolute light yield of BGO, without the assumption of absence of traps, and the light collection efficiency of its optical bolometer. From these values we have also estimated the energy partition (fraction of energy that goes into heat, light and traps) of both scintillating bolometers: Sapphire and BGO. The experimental set–up used in the study of the BGO scintillation spectra, the performed measurements and the results derived therefrom are discussed in the next sections.

2. BGO scintillation spectra

At IAS we have performed systematic measurements of the BGO scintillation spectra under x–ray excitation from room temperature down to 77 K. Figure 3 shows the experimental set-up used in these measurements. A small BGO crystal has been irradiated with photons from an x–ray tube (40 kV and 98 μA). The BGO crystal studied was a disk (2.06 mm thickness and 19.8 mm in diameter) mounted inside a copper holder (6 mm height and 21 mm in diameter) with the internal reflecting cavity coated with Ag (a similar mounting to that used in our scintillating bolometers). The holder was located inside a cryostat with a Be window for x–ray irradiation. A thin Al foil on the top of the holder cavity was also facing to the Be window to allow photons from the x–ray tube to reach the crystal. Scintillation photons were collected with an Avantes optical fiber UV 0706058 (2 m length, 1 mm in diameter, spectral band between 370 and 1070 nm and numerical aperture $NA = 0.22$) coupled to the crystal cavity, and transmitted to an Avantes Fiber Spectrometer 2048 TEC where they were diffracted with a grating plane VA (VIS/NIR) of 300 lines/mm and registered with a CCD detector. Figure 4 shows the BGO scintillation spectra measured at different temperatures while the BGO crystal was cooled from room temperature down to 77 K. These spectra show that the number of scintillation photons emitted under x–ray excitation increases as the temperature decreases and that at the lowest

temperatures (below 150 K) tends to a constant value in agreement with the behavior reported in [15] where the scintillation light response of BGO was measured down to a temperature of 6 K. In reference [15], taking the light yield of BGO at room temperature to be 6900 ± 140 photons/MeV [16], they have estimated that the BGO light yield has a value of 23700 ± 2600 photons/MeV[1] at 6 K. In figure 4 can be also observed a change in the shape of the spectra: the relative amplitude of the second peak at around 550 nm increases as temperature decreases and, as happens with the total light output, there is no noticeable change at the lowest temperatures (below 150 K).

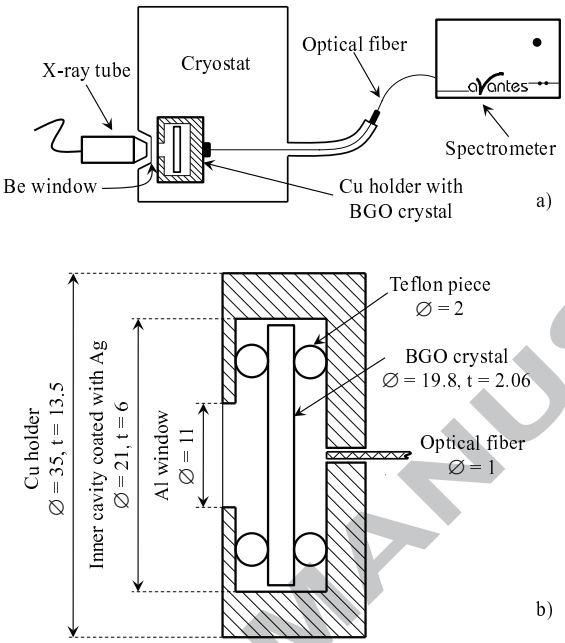

Figure 3: a) Experimental set-up of the cryostat and the crystal holder used for measuring the BGO emission spectra at different temperatures. b) Detail of the Cu holder with the BGO crystal. Here ∅ and t stand for, respectively, the diameter and thickness dimensions (given in mm) of the different components.

From the measured spectrum $I_m(\lambda)$ at 77 K, shown in figure 4, we can estimate the relative intensity of scintillation photons emitted $n(\lambda)$ at this temperature as

$$n(\lambda) = \frac{I_m(\lambda)}{\eta_c(\lambda) \cdot \eta_f(\lambda) \cdot \eta_g(\lambda) \cdot S_s(\lambda)} \tag{1}$$

where λ is the wavelength, η_c, η_f and η_g are the transmission efficiencies of the crystal cavity, of the optical fiber and of the diffraction grating, respectively, and S_s is the spectral relative sensitivity of the CCD detector (data on S_s are only available from 400 nm to 700 nm but it practically covers the full BGO emission spectrum). Figure 5 shows the dependence with λ of these four correction coefficients. Three of them (η_f, η_g and S_s) have been taken from the manufacturer's datasheets. The cavity transmission efficiency, η_c, is defined as the ratio between the light collected by the optical fiber $I_c(\lambda)$ and that emitted by the crystal $I_e(\lambda)$. This coefficient can be estimated in a simple model by

$$\eta_c(\lambda) = \frac{I_c(\lambda)}{I_e(\lambda)} = x + R(\lambda) \cdot (1 - x) \cdot \varphi \cdot \sum_{n=0}^{\infty} R^n(\lambda) \cdot (1 - \varphi)^n \tag{2}$$

$$\eta_c(\lambda) = x + \frac{R(\lambda) \cdot \varphi}{1 - R(\lambda) \cdot (1 - \varphi)} \cdot (1 - x) \tag{3}$$

[1]Notice that this value is consistent with that obtained at 77 K in [16] supporting the observed independence with temperature of the light yield below 100 K.

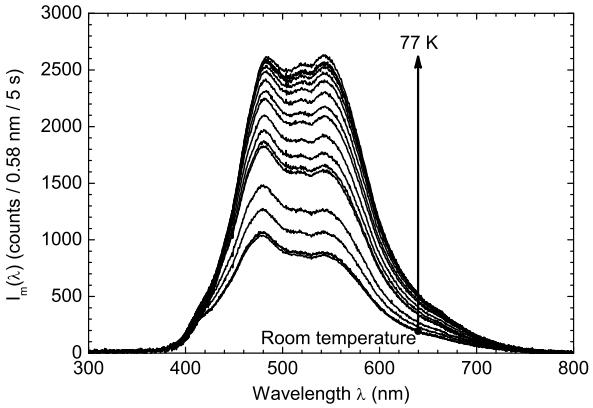

Figure 4: BGO differential scintillation spectra $I_m(\lambda)$ measured at different temperatures from room temperature down to 77 K with an x–ray excitation source. All measurements were made with an integration time in the spectrometer of 5 s. Intermediate measurements were performed dynamically while the cryostat was cooling down, measuring the temperature of the surroundings of the crystal. These values are not given because they do not reflect the exact temperature of the crystal (it could be hotter). The last three-four intermediate spectra (with surroundings temperatures around 130–160 K) and the 77 K spectrum show that there is no noticeable change in shape.

where the first term, x, represents the fraction of light directly collected by the optical fiber and the second one, the light collected after successive reflections in the cavity, being $R(\lambda)$ the reflectivity of the cavity coating [17] (also shown in figure 5) and φ the probability that a photon reaches the fiber with a correct angle for transmission. With our geometry we have $x = \frac{S_f}{S_c}\frac{\Omega_f}{\Omega_c}$ and $\varphi = \frac{S_f}{S_c}\frac{\Omega_f}{2\pi}$, where S_f is the cross section of the optical fiber, S_c is the cavity total area, $\Omega_f \approx \pi \cdot NA^2$ is the solid angle for transmission of photons by the fiber and Ω_c is the solid angle subtended by the crystal at the optical fiber position.

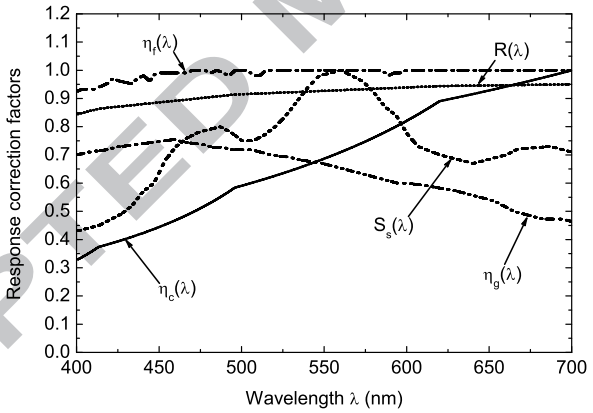

Figure 5: Transmission efficiencies of the crystal cavity (η_c), of the optical fiber (η_f), and of the diffraction grating (η_g), and spectral relative sensitivity of the CCD detector of the spectrometer (S_s) as a function of the wavelength. Also shown is the Ag reflectivity $R(\lambda)$ [17] used for the η_c estimate.

Values derived for $\eta_c(\lambda)$ from equation 3 (normalized to one for 700 nm) are shown in figure 5. Figure 6 shows the measured scintillation spectrum $I_m(\lambda)$ of BGO at 77 K (raw data) and the relative intensity of scintillation photons $n(\lambda)$ emitted at this temperature (corrected data) as obtained from equation 1 and normalized to $I_m(\lambda)$ area. The average energy of BGO scintillation photons at 77 K can be estimated from $n(\lambda)$ as

$$\langle E \rangle = hc\left\langle \frac{1}{\lambda} \right\rangle = hc\left\{ \frac{1}{N}\sum_{\lambda=\lambda_i}^{\lambda_f} \frac{1}{\lambda}\cdot n(\lambda) \right\} \tag{4}$$

where $N = \sum_{\lambda=\lambda_i}^{\lambda_f} n(\lambda)$ and, in our case, $\lambda_i = 400$ nm and $\lambda_f = 700$ nm. We estimate a value of $\langle E \rangle = 2.436 \pm 0.017_{stat} \pm 0.068_{syst}$ eV, where the systematic error is introduced to take into account the small effects produced by the presence of the teflon pieces and the Al foil on top of the holder cavity, and also by the crystal autoabsorption. It has been estimated as the difference between the mean energy obtained with and without the correction factors inclusion (2.436 ± 0.017 eV and 2.368 ± 0.017 eV). Assuming that, as reported by [15, 18], below 100 K the scintillation response remains practically constant and, as suggested by our results shown in figure 4, the BGO scintillation spectrum practically does not change at low temperatures, we can take this value as the average energy of BGO scintillation photons below 100 K and, in particular, at 20 mK (the operation point of our bolometers). In fact, our estimate of $\langle E \rangle$ is in good agreement with studies of BGO luminescence at temperatures of a few Kelvin: for instance, in [19] operating at 10 K they report a broad luminescence band at 2.46 eV, whereas in [20] they observe at 5 K an intense emission band at around 510 nm (2.43 eV). This comparison suggests that practically the same scintillation mechanism and, consequently, the same scintillation response are observed in the different BGO crystals analyzed in the literature (see for instance [21–23]).

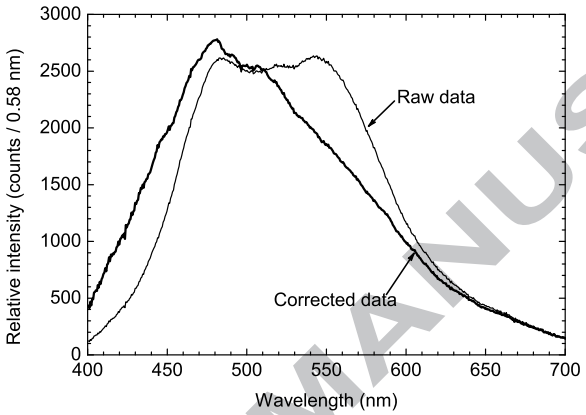

Figure 6: Raw data stands for the measured spectrum $I_m(\lambda)$ for BGO at 77 K and corrected data for the relative intensity of scintillation photons emitted at this temperature (obtained after corrections explained in the text and normalized to the same area of $I_m(\lambda)$).

3. Light yield and energy partition in scintillating bolometers

From the average energy of BGO scintillation photons $\langle E \rangle$ estimated in the previous section and the BGO light yield of 23700 ± 2600 photons/MeV at 6 K quoted by [15], we obtain that the absolute light yield of the BGO at 20 mK is $\alpha_\ell = 0.058 \pm 0.006_{stat} \pm 0.002_{syst}$.

Carrying out an absolute energy calibration of the light signal with an inner ^{55}Fe x–ray source placed opposite to the optical Ge bolometer of the BGO scintillating bolometer, we can also estimate its light collection efficiency. We have observed that an x–ray photon of 5.9 keV from the ^{55}Fe source fully absorbed in the Ge bolometer produces the same light pulse amplitude that a photon of 841.3 ± 8.3 keV fully absorbed in the BGO scintillating crystal. Neglecting the fraction of the x–ray energy lost in traps in the Ge target, we derive an equivalent light energy of 7.01 ± 0.07 keV/MeV and a light collection efficiency of $0.121 \pm 0.013_{stat} \pm 0.004_{syst}$ for the double bolometer mounting. Notice that the Ge bolometer shows an excellent linearity as optical detector of the BGO in the range from 88 to 1633.3 keV [24].

In the case of the Sapphire bolometer, since we do not have a measurement of the absolute light yield at low temperatures (of the order of a few Kelvin) for this Ti concentration (measurements at 9 K for others Ti concentration are given in [25]), we do conversely: from the light collection efficiency we estimate the absolute light yield. Since both scintillating bolometers have a very similar geometry, reflecting cavity (Ag–coated Cu) and optical detector, we have assumed that light collection efficiency is the same. On the assumption that Ag reflectivity (ranging from 85 to 95%, as shown in figure 5) is the dominant effect, influence of the different detector material and surface has been neglected. The absolute energy calibration of the optical Ge bolometer of the Sapphire scintillating bolometer with

the ^{55}Fe x–ray source leads to an equivalent light energy detected of 13.5 ± 0.3 keV/MeV and, consequently, to an absolute light yield $\alpha_\ell = 0.112 \pm 0.012_{stat} \pm 0.004_{syst}$.

Finally, from the values of the absolute light yields and those derived for α_ℓ/α_h (see table 1), given that $\alpha_\ell + \alpha_h + \alpha_0 = 1$ (where α_0 is the fraction of deposited energy trapped), it is straightforward to estimate the deposited energy partition after photon interactions in Al_2O_3 and BGO scintillating bolometers (see table 2). Absolute light yield of Sapphire is twice that of BGO, whereas the trapping fraction is four times smaller. Notice that the scintillation yield of this Sapphire (≈11%) is comparable with the values obtained with the most pre–eminent materials used as scintillation detectors at room temperature (for instance, thallium-activated sodium iodide reports light yield of about ≈12% [26]). This light response converts this sapphire into an excellent detector with particle discrimination capability down to energies of about 10 keV [27]. The high α_ℓ value of this Sapphire can be attributed, according to reference [28], to the presence of Ti in the crystal lattice.

Table 2: Energy partition in Sapphire and BGO scintillating bolometers for γ–ray interactions. Here are shown values obtained for the fraction of energy deposited that initially is converted into light (α_ℓ), heat (α_h) or trapped (α_0). The first and second errors given correspond to the statistic and systematic ones, respectively.

	Al_2O_3	BGO
α_ℓ	0.112 ± 0.012 ± 0.004	0.058 ± 0.006 ± 0.002
α_h	0.778 ± 0.099 ± 0.028	0.464 ± 0.092 ± 0.016
α_0	0.110 ± 0.100 ± 0.028	0.478 ± 0.092 ± 0.016

4. Conclusions

We have measured the scintillation spectra of BGO at different temperatures from room temperature to 77 K. From these spectra we have observed that the light output of the crystal increases and the spectral shape changes when cooling down. However, at the lowest temperatures both the light output and the spectral shape remain practically constant. Under this assumption, we have derived an average energy of $2.436 \pm 0.017_{stat} \pm 0.068_{syst}$ eV for scintillation photons emitted by BGO at low temperatures. This value allows us to estimate the absolute light yield ($\alpha_\ell = 0.058 \pm 0.006_{stat} \pm 0.002_{syst}$) and the light collection efficiency ($0.121 \pm 0.013_{stat} \pm 0.004_{syst}$) of the BGO scintillating bolometer and, indirectly, under the assumption of identical light collection efficiency, the absolute light yield of the Sapphire ($\alpha_\ell = 0.112 \pm 0.012_{stat} \pm 0.004_{syst}$). Combining these results with the ratio α_ℓ/α_h, obtained from the negative correlation found between the light and heat responses in Sapphire and BGO scintillating bolometers, we have estimated the energy partition produced in both detectors for photon interactions: the fraction of deposited energy that initially goes into light, heat and traps.

Acknowledgments

This work has been supported by the Spanish Ministerio de Ciencia e Innovación (MICINN) (FPA2008–03228 and MULTIDARK Consolider CSD2009–00064), the French CNRS/INSU (MANOLIA and BOLERO projects) and the EU project ILIAS (RII3–CT–2004–506222). Y. Ortigoza was also supported by a UZ/BSCH/Fundación Carolina grant and by a DECRYPT (Detectores de Radiación y Partículas) investigation project contract. L. Torres is supported by a MICINN postdoctoral grant.

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